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**Abstract:**

As part of the Accelerator Production of Tritium (APT) and the Spallation Neutron Source Programs, the tensile properties of annealed 304L, 316LN and 316L stainless steel have been measured after proton and spallation neutron irradiation in the target region of the Los Alamos Neutron Science Center (LANSCE) accelerator (800 MeV, 1 mA) to a maximum dose of 12 dpa at temperatures ranging from 30ºC to 120ºC. In addition to the displacement damage produced from the irradiation, up to several thousand atomic parts per million (appm) of hydrogen and helium were produced in the irradiated material via spallation reactions. Results of tensile tests at temperatures from room temperature up to 164ºC show large increases in tensile yield strength, small increases in ultimate tensile strength, reductions in strain hardening capacity and reductions in ductility (uniform elongation and strain-to-necking) with increasing irradiation dose. A comparison of these data with the large database on tensile properties of type 316 stainless steel exposed to fission neutrons and tensile tested over the same temperature range show similar trends with regard to strength changes, but significantly larger reductions in ductility with irradiation dose were observed in the spallation environment. The much higher amounts of helium and hydrogen produced through spallation in the LANSCE spectrum, compared to those developed in fission neutron irradiation environments at equivalent doses, may contribute to degradation in ductility.

**Keywords:** tensile testing, radiation effects, Accelerator Production of Tritium (APT), stainless steel, 316L, 304L

**Introduction:**

Because of recent high energy proton accelerator projects such as the Spallation Neutron Source (SNS) project at Oak Ridge National Laboratory (ORNL) [1], the JAERI Spallation Source program [2], the European Spallation Source program (ESS) [3], and the Accelerator Production of Tritium (APT) Project [4], there is considerable interest in the effect of high energy protons and spallation neutrons on the mechanical properties of structural materials. Although there is a large database on the effect of irradiation on the mechanical properties of structural materials in a fission neutron flux, there is very little tensile data on materials irradiated in a high energy proton and spallation neutron flux. Thus it is tempting to use the fission neutron tensile properties database to design structures for use in a high energy proton/spallation neutron environment. Unfortunately, there are some significant differences expected from irradiation in a high energy proton and spallation neutron flux. Irradiations at energies greater than 20 MeV cause higher primary knock-on energies, larger displacement cascades, and significantly increased generation of hydrogen and helium.

To investigate the effect of high energy protons and spallation neutrons on the mechanical properties of structural metals, a large irradiation experiment was conducted at the LANSCE 800 MeV proton accelerator [5] in support of the Accelerator Production of Tritium Project. During this irradiation, tensile specimens of annealed 316L and 304L stainless steel were irradiated to doses up to 12 dpa at irradiation temperatures from 30ºC to 120ºC and were tested at temperatures from room temperature to 164ºC [6, 7]. A significant reduction in uniform elongation was observed which was sensitive to test temperature and appears to be markedly different from data observed after irradiation at similar temperatures/doses in a fission reactor.

In this paper, a comparison is made between data measured after irradiation in a high energy proton and spallation neutron spectra and that measured after irradiation in a fission neutron environment.

**Experimental:**

S-1 tensile specimens (Figure 1) of 316L, 316LN and 304L stainless steel were electro-discharge machined from two thicknesses of sheet material, 0.25 and 0.75 mm. The materials were received in the annealed form, and no further heat treatment was performed. More details on the preparation of these specimens can be found in References [6] and [7]. The tensile specimens were irradiated for six months in special thin encapsulated specimen holders in the mixed proton/spallation neutron beam at the LANSCE accelerator to a maximum dose of 12 dpa. After irradiation, the dose for each specimen was determined from analysis of high-purity activation foils placed next to specimens during irradiation. Details of the dose determination can be found in Reference [8]. The temperature for each specimen was determined by calculations that used measurements from thermocouples placed near each specimen to determine gap resistances between samples and specimen holder cover plates. The details of this temperature measurement can be found in Reference [9]. The irradiated specimens were tensile tested at an initial strain rate of $10^{-4}$/s in air using an Instron machine equipped with a high temperature furnace. See References [6] and [7] for more details.

**Results:**

Representative engineering stress/strain curves for 316L, 316LN and 304L stainless steel specimens irradiated and tested at 50°C are shown in Figure 2. These curves show irradiation-induced increases in yield strength, losses in ductility and reductions in work hardening capacity.

Companion true stress vs. true strain curves for selected irradiated specimens are plotted in Figure 3. These curves also show a significant decrease in ductility with irradiation. Using these curves, one can determine the true strain to plastic instability. This is the point at which the rate of increase in material strength ($d\sigma/d\varepsilon$) can no longer offset the rate of loss of load carrying capacity, i.e. when

$$\sigma = \frac{d\sigma}{d\varepsilon}$$

where $\sigma$ equals the true stress. These data are plotted in Fig. 4 for 316L and 316LN stainless steel specimens tested at 25, 50 and 164ºC. Clearly, a significant dependence of ductility on test temperature is observed in this data. See Reference [10] for more details.

Unfortunately, true strain to plastic instability has not been measured on most of the samples for previously published data on the effect of fission neutron irradiation on the mechanical properties of 316 or 304 stainless steel. Generally, either uniform elongation or strain-to-necking (STN) has been measured. STN is generally equal to uniform elongation except in very few cases where the maximum load does not coincide with the maximum elongation before necking occurs. To compare to previous fission reactor data, strain-to-necking is plotted vs. dose in Fig. 5 for 316L/304L after irradiation in a proton beam. Curve fits are drawn for each test temperature to show trends only. As shown in previous plots, a steeper drop in STN is observed with dose as test temperature is increased from 25 to 164ºC. Figure 6 also shows the variation in yield stress with dose for 304L and 316L after irradiation in a high energy proton beam. The yield stress is observed to decrease slightly with increasing test temperature from 25 to 164ºC.

To look at the effect of specimen thickness on these measured properties, Figure 7 shows a plot of STN vs. dose for 0.75 mm and 0.25 mm thick specimens. A drop in ductility as a function of dose is observed for both thicknesses of specimens, however the thicker specimens appear to have slightly better resistance to necking for doses up to 4 dpa. This may be a specimen geometry effect, but it could also be due to the fact that these 0.25 mm and 0.75 mm thick specimens were fabricated from two different heats of material. This trend showing decreasing STN with decreasing thickness agrees with previous results on this S-1 specimen geometry [11].

**Comparison:**

In order to compare the proton/spallation neutron irradiation measurements with results from irradiation in a fission reactor, a literature review was performed to find tensile data on specimens irradiated in a fission reactor at irradiation and test temperatures from 25 to 220ºC [12-21]. These results along with the measured results from the LANSCE irradiation are shown in Tables 1 and 2. The irradiation temperature for the neutron data ranges from 30 to 220ºC. In general, tests were performed at or close to the irradiation temperature. It is interesting to note that although there is a large tensile properties database for irradiation in a fission neutron spectrum, the amount of data measured in the 25 to 220ºC temperature range is small. Generally, most of the specimens had a gage length of 18-20 mm with either a thickness of 0.767 mm or a diameter of 2-4 mm.

A graphical comparison of uniform elongation or STN vs. dose for irradiation in a fission neutron and proton/spallation neutron spectra is shown in Figure 8 for test temperatures of 25ºC, 50-80ºC and 164-220ºC. For tests at 25ºC, trends for irradiation in a fission spectrum are the same as for a proton/spallation neutron spectrum. STN values remain above 10% to doses of 10

dpa (LANSCE) and 20 dpa (fission). But for testing at 50-80ºC, STNs greater than 10% are retained for irradiation in a fission neutron spectrum for doses up to 10 dpa, whereas for irradiation in a proton/spallation neutron spectrum STNs fall sharply to <1% at doses between 2 and 4 dpa. Similarly for tests at 164ºC in a proton/spallation neutron spectrum, STNs reach <1% at a dose of 2-4 dpa, but at 200-220ºC in a fission neutron spectrum, STNs of less than 1% STN are not observed until a dose of greater than 15 dpa. Unfortunately, there were no tests performed on fission spectrum specimens irradiated between 7 and 16 dpa at 200-220ºC, so it is possible that the STN could be less than 1% at doses as low as 7-8 dpa in a fission neutron spectrum. A graphical comparison of yield stress vs. dose for irradiation in a fission neutron and proton/spallation neutron spectrum is shown in Figure 9. The data do seem to show similar trends for both fission and proton/spallation neutron spectra where higher yield stresses are observed for testing at decreasing temperature from 220 down to 25ºC.

**Discussion:**

This comparison between tensile properties measured after irradiation in a fission vs. proton/spallation neutron spectrum does seem to show some differences in STN at test temperatures from 50-220ºC. There are some differences in specimen dimensions and geometries to which this could be attributed. For example, the specimens tested after irradiation in a fission neutron spectrum have thicknesses equal or greater than 0.76 mm. In comparison, the specimens irradiated in a proton/spallation neutron spectrum were 0.25 and 0.75 mm thick, but the data from these specimens only showed a shift of one dpa in the dose at which STN dropped to less than 1%. A critical geometrical factor for comparing elongations is $L_o/(A_o^{1/2}$ or $D_o)$ [22] where $L_o$ equals gage length, $A_o$ equals cross-sectional area and $D_o$ equals diameter. Values are shown in Table 1 for the specimens irradiated in a fission neutron spectrum. For the

LANSCE irradiated specimens, the geometry factor ranges from 9.1 to 5.3, whereas for the fission neutron irradiated specimens it ranged from 5 to 18.9 but specimens with similar geometrical factors still show higher STN values for irradiation in a fission neutron spectrum. There are also possible heat-to-heat variations but these differences appear very small since the LANSCE data is from four different heats of materials while the fission neutron data is from seven different heats of materials and all data were quite consistent.

One clear difference between the specimens irradiated in a fission neutron spectrum and those irradiated in a proton/spallation neutron spectrum is the large amount of gas produced from spallation in the LANSCE irradiated specimens. Table 2 shows calculated values for all specimens. These values have been confirmed to be about a factor of two low for helium and a factor of five high for hydrogen measurement (much of the hydrogen is lost by recoil and diffusion) performed on irradiated specimens. Of the specimens irradiated in a fission neutron spectrum, only three have high amounts of helium (1000-2000 appm). Two of these were tested at 25ºC, and the results show high uniform elongation values of ~15% after 26 dpa of exposure [17]. On the other hand, a specimen irradiated to 16 dpa, containing 1064 appm He and tested at 200ºC, produced a uniform elongation of only 0.39% [18]. Therefore, this does not rule out the possible effect of helium on STN. Nor does it include a possible contribution from radiation-produced hydrogen. Recent results by Snead et al. [23] showed that a reduced fracture toughness was observed in the same heat of 304L irradiated to 1.5 dpa in the High Flux Isotope Reactor compared to the fracture toughness measured after irradiation in LANSCE, while no difference in fracture toughness was observed for the 316L specimen irradiated to 1.5 dpa.

**Conclusions:**

The tensile properties of 316L/304L have been measured after irradiation in the LANSCE high energy proton beam and are summarized below:

– The true strain to plastic instability at 6 dpa is 1%, 3% and 18% at 164, 50 and 25ºC respectively after irradiation in a high energy proton beam.

– STN and yield stress of irradiated specimens decreased with increasing test temperature between room temperature and 164ºC.

These results have been compared to results for irradiation of 316L/304L stainless steel in a fission reactor spectrum.

–STN values measured at 25ºC (above 10 dpa), 50-80ºC and 164-220ºC are lower after irradiation in a high energy proton beam than after irradiation in a fission reactor.

– The change in yield stress with dose measured after irradiation in a high energy proton beam shows good agreement with yield stress measured after irradiation in a fission reactor.

–High gas levels of helium or hydrogen appear to cause reduced ductility in spallation environments.

These results suggest that further research should be performed using the same types of tensile specimens and the same heat of material to confirm the comparative behavior of the effects of irradiation in a fission neutron spectrum to those measured in a spallation spectrum.

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Table 1 Tensile Property data measured on 316/304 Stainless Steel after irradiation in a Fission Neutron Spectrum

| Alloy | Irrad. Temp (C) | Test Temp (C) | Dose (dpa) | He (appm) | UE (%) | STN | TE (%) | YS (MPa) | UTS (MPa) | Reference | gage length (mm) | Thickness or Diam. (mm) | Geom. Factor |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 316 SA | 60 | 25 | 7-8 | 100 | 24.5 | | 29.9 | 703 | 752 | Grossbeck | 20.3 | 0.762 | 18.9 |
| 316 SA | 60 | 25 | 7-8 | 100 | 27.6 | | 32.5 | 690 | 745 | Grossbeck | 20.3 | 0.762 | 18.9 |
| 304 | 200 | 204 | 1.05 | | 9.4 | | 14.8 | 645 | 718 | martin STP | 28.6 | 3.2 diam | 8.9 |
| SA J316 | 60 | 25 | 6.9 | 75 | 25 | 26.1 | 30 | 703 | 752 | Pawel FRM | 20.3 | 0.762 | 18.9 |
| SA J316 | 60 | 25 | 6.9 | 75 | 28 | 29.9 | 33 | 690 | 745 | Pawel FRM | 20.3 | 0.762 | 18.9 |
| SA J316 | 200 | 200 | 6.9 | 75 | 0.2 | 13.6 | 15.9 | 758 | 765 | Pawel FRM | 20.3 | 0.762 | 18.9 |
| SA J316 | 200 | 200 | 6.9 | 75 | 12 | 12 | 15 | 733 | 737 | Pawel FRM | 20.3 | 0.762 | 18.9 |
| SA J316 | 60 | 25 | 19 | 190 | 20 | 22.2 | 25 | 716 | 743 | Pawel FRM | 20.3 | 0.762 | 18.9 |
| SA J316 | 60 | 25 | 19 | 190 | 20 | 23.3 | 26 | 747 | 765 | Pawel FRM | 20.3 | 0.762 | 18.9 |
| SA J316 | 60 | 330 | 19 | 190 | 10 | | 13 | 596 | 614 | Pawel FRM | 20.3 | 0.762 | 18.9 |
| SA J316 | 200 | 200 | 17 | 197 | 0.2 | 3.4 | 5.7 | 745 | 752 | Pawel FRM | 20.3 | 0.762 | 18.9 |
| SA J316 | 200 | 200 | 17 | 197 | 0.2 | 7.2 | 9.8 | 740 | 740 | Pawel FRM | 20.3 | 0.762 | 18.9 |
| JPCA SA | 200 | 200 | 7 | | 8.2 | | 11 | 700 | 700 | Shiba FRM | 7.62 | 0.762 | 7.1 |
| JPCA SA | 200 | 200 | 18 | | 0.2 | | 5.2 | 710 | 720 | Shiba FRM | 7.62 | 0.762 | 7.1 |
| JPCA-SA | 55 | 25 | 26 | 2008 | 14.2 | | 16.8 | 822 | 834 | Jitsukawa, | 20.3 | 0.762 | 18.9 |
| J316-SA | 55 | 25 | 26 | 1506 | 15.7 | | 18.1 | 693 | 709 | Jitsukawa, | 20.3 | 0.762 | 18.9 |
| JPCA-SA | 200 | 200 | 16 | 1064 | 0.39 | | 8.6 | 876 | 889 | Hishunama | 18.3 | 2 mm diam | 9.15 |
| 316L(N) | 80 | 80 | 0.7 | ~21 | 22.5 | | 40.5 | 565 | 650 | Horsten, A | 20 | 4 mm diam | 5 |
| 316L(N) | 80 | 80 | 5 | ~50 | 21.5 | | 36 | 610 | 690 | Horsten, A | 20 | 4 mm diam | 5 |
| 316 | 35 | 55 | 5.5 | 180 | 23.5 | | 30.2 | 799 | 841 | Wiffen, JN | 18.3 | 2 mm diam | 9.15 |
| 316 | 35 | 300 | 4.5 | 180 | 16.2 | | 20.9 | 526 | 629 | Wiffen, JN | 18.3 | 2 mm diam | 9.15 |
| 316LN | 227 | 77 | 10 | 140 | | 10 | 19 | 930 | 930 | Horsten, J | 20 | 4 mm diam | 5 |
| 316LN | 227 | 25 | 10 | 140 | | 11 | 21 | 1010 | 1010 | Horsten, J | 20 | 4 mm diam | 5 |

Table 2 Tensile Property Data for 316/304 Stainless Steel after Irradiation in a Spallation Spectrum

| Alloy | ID | He (appm) | H (appm) | Thickness (mm) | Dose (dpa) | Irrad. Temp (C) | Test temp (C) | YS (MPa) | UTS (MPa) | UE (%) | TE (%) | STN |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 316L | 316-9 | | | 0.75 | 0.0 | | 50 | 255 | 598 | 51.4 | 76.3 | 51.4 |
| 316L | 316-10 | | | 0.75 | 0.0 | | 50 | 259 | 593 | 51.3 | 72.6 | 51.3 |
| 316L | 316-11 | | | 0.75 | 0.0 | | 164 | 221 | 485 | 32.2 | 52.1 | 32.2 |
| 316L | 316-12 | | | 0.75 | 0.0 | | 164 | 221 | 486 | 32.1 | 50.6 | 32.1 |
| 316L | 1A1a | | | 0.25 | 0.1 | 74 | 50 | 603 | 726 | 22.9 | 34.8 | 22.9 |
| 316L | 1A1b | | | 0.25 | 0.1 | 74 | 50 | 503 | 730 | 20.2 | 33.2 | 20.2 |
| 316L | 2A7a | | | 0.25 | 0.1 | 114 | 50 | 571 | 765 | 20.4 | 31.3 | 20.4 |
| 316L | 2A7b | | | 0.25 | 0.1 | 114 | 50 | 556 | 741 | 23.3 | 32.0 | 23.3 |
| 316L | 2A8c | | | 0.25 | 0.1 | 114 | 50 | 546 | 703 | 22.4 | 31.1 | 22.4 |
| 316L | 3A11a | | | 0.25 | 0.1 | 98 | 50 | 607 | 769 | 22.1 | 33.2 | 22.1 |
| 316L | 3A11b | | | 0.25 | 0.1 | 98 | 50 | 547 | 737 | 22.7 | 30.2 | 22.7 |
| 316L | 2A7c | | | 0.25 | 0.1 | 114 | 50 | 595 | 761 | 20.5 | 30.8 | 20.5 |
| 316L | 9A17a | | | 0.25 | 0.0 | 127 | 50 | 589 | 734 | 20.8 | 28.2 | 20.8 |
| 316L | 9A17b | | | 0.25 | 0.0 | 127 | 50 | 501 | 713 | 23.0 | 34.6 | 23.0 |
| 316L | 10A26a | | | 0.25 | 0.1 | 105 | 50 | 523 | 699 | 25.6 | 34.6 | 25.6 |
| 316L | 10A26b | | | 0.25 | 0.1 | 105 | 50 | 568 | 734 | 24.7 | 35.2 | 24.7 |
| 316L | 10A26c | | | 0.25 | 0.1 | 105 | 20 | 649 | 769 | 23.4 | 39.8 | 23.4 |
| 316L | 10A26d | | | 0.25 | 0.1 | 105 | 20 | 562 | 761 | 23.0 | 39.2 | 23.0 |
| 316L | 10A26c | | | 0.25 | 0.1 | 105 | 22 | 562 | 761 | 23.0 | 39.2 | 23.0 |
| 316L | 10A26d | | | 0.25 | 0.1 | 105 | 22 | 649 | 769 | 23.4 | 39.8 | 23.4 |
| 304L | 2-6-1 | 51 | 429 | 0.25 | 0.8 | 33 | 50 | 559 | 746 | 30.2 | 45.5 | 30.2 |
| 304L | 2-6-2 | 52 | 435 | 0.25 | 0.8 | 33 | 50 | 550 | 707 | 30.2 | 43.4 | 30.2 |
| 304L | 2-6-5 | 426 | 3627 | 0.25 | 5.9 | 56 | 50 | 829 | 837 | 0.3 | 22.5 | 0.3 |
| 304L | 2-6-6 | 556 | 4714 | 0.25 | 7.5 | 56 | 50 | 791 | 822 | 0.9 | 19.2 | 0.9 |
| 304L | 2-6-12 | 52 | 435 | 0.25 | 0.8 | 33 | 164 | 460 | 554 | 17.8 | 26.0 | 17.8 |
| 304L | 2-6-11 | 51 | 429 | 0.25 | 0.8 | 33 | 164 | 446 | 536 | 20.3 | 30.5 | 20.3 |
| 304L | 2-6-7 | 445 | 3783 | 0.25 | 6.2 | 57 | 164 | 723 | 738 | 0.4 | 10.3 | 0.4 |
| 304L | 2-6-8 | 581 | 4923 | 0.25 | 7.8 | 57 | 164 | 734 | 738 | 0.3 | 9.6 | 0.3 |
| 304L | 22-5-7 | 241 | 2164 | 0.25 | 3.9 | 48 | 50 | 735 | 759 | 0.7 | 35.8 | 26.5 |
| 304L | 22-5-8 | 255 | 2275 | 0.25 | 4.0 | 48 | 50 | 761 | 788 | 0.7 | 33.4 | 24.2 |
| 304L | 22-5-5 | 181 | 1561 | 0.25 | 2.9 | 42 | 50 | 687 | 717 | 27.3 | 43.3 | 27.3 |
| 304L | 22-5-6 | 192 | 1643 | 0.25 | 3.0 | 42 | 50 | 739 | 783 | 25.9 | 40.9 | 25.9 |
| 304L | 22-5-9 | 168 | 1460 | 0.25 | 2.7 | 43 | 164 | 518 | 572 | 9.0 | 18.7 | 9.0 |
| 304L | 22-5-10 | 178 | 1536 | 15 0.25 | 2.8 | 43 | 164 | 581 | 586 | 7.2 | 17.1 | 7.2 |

| Alloy | ID | He (appm) | H (appm) | Thickness (mm) | Dose (dpa) | Irrad. Temp (C) | Test temp (C) | YS (MPa) | UTS (MPa) | UE (%) | TE (%) | STN |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 304L | 2-7-6 | 513 | 4351 | 0.75 | 7.0 | 90 | 22 | 929 | 981 | 0.9 | 21.2 | 17.0 |
| 304L | 22-6-11 | 46 | 409 | 0.75 | 0.9 | 42 | 50 | 638 | 782 | 36.7 | 54.6 | 36.7 |
| 304L | 22-6-12 | 50 | 434 | 0.75 | 0.9 | 42 | 50 | 675 | 794 | 30.0 | 46.9 | 30.0 |
| 304L | 22-6-9 | 156 | 1349 | 0.75 | 2.5 | 52 | 80 | 703 | 760 | 18.6 | 35.3 | 18.6 |
| 304L | 22-6-10 | 166 | 1420 | 0.75 | 2.6 | 52 | 80 | 737 | 793 | 22.7 | 41.9 | 22.7 |
| 304L | 22-6-7 | 241 | 2163 | 0.75 | 3.9 | 75 | 164 | 674 | 733 | 0.8 | 19.3 | 0.8 |
| 304L | 22-6-8 | 255 | 2275 | 0.75 | 4.0 | 75 | 164 | 687 | 738 | 0.7 | 18.7 | 0.7 |
| 304L | 304-1 | | | 0.25 | 0.0 | | 20 | 309 | 633 | 63.2 | 79.3 | 63.2 |
| 304L | 304-2 | | | 0.25 | 0.0 | | 20 | 359 | 613 | 61.1 | 73.5 | 61.1 |
| 304L | 304-6 | | | 0.25 | 0.0 | | 50 | 229 | 587 | 56.8 | 71.0 | 56.8 |
| 304L | 304-7 | | | 0.25 | 0.0 | | 50 | 271 | 574 | 58.2 | 71.1 | 58.2 |
| 304L | 304-9 | | | 0.25 | 0.0 | | 164 | 213 | 482 | 24.6 | 37.7 | 24.6 |
| 304L | 304-10 | | | 0.25 | 0.0 | | 164 | 238 | 479 | 33.7 | 46.5 | 33.7 |
| 304L | 304-3 | | | 0.75 | 0.0 | | 20 | 299 | 719 | 62.3 | 84.6 | 62.3 |
| 304L | 304-11 | | | 0.75 | 0.0 | | 20 | 301 | 697 | 72.6 | 100.5 | 72.6 |
| 304L | 304-4 | | | 0.75 | 0.0 | | 50 | 281 | 649 | 57.2 | 74.3 | 57.2 |
| 304L | 304-12 | | | 0.75 | 0.0 | | 50 | 279 | 634 | 64.7 | 80.8 | 64.7 |
| 304L | 304-5 | | | 0.75 | 0.0 | | 164 | 216 | 509 | 37.4 | 54.9 | 37.4 |
| 304L | 304-13 | | | 0.75 | 0.0 | | 164 | 227 | 510 | 38.7 | 56.8 | 38.7 |
| 304L | 1A4a | | | 0.25 | 0.1 | 74 | 50 | 502 | 676 | 35.7 | 45.4 | 35.7 |
| 304L | 1A4b | | | 0.25 | 0.1 | 74 | 50 | 474 | 688 | 31.8 | 48.3 | 31.8 |
| 304L | 2A9b | | | 0.25 | 0.1 | 114 | 50 | 520 | 685 | 34.2 | 46.3 | 34.2 |
| 304L | 2A9c | | | 0.25 | 0.1 | 114 | 50 | 529 | 698 | 35.2 | 46.1 | 35.2 |
| 304L | 3A14a | | | 0.25 | 0.1 | 98 | 50 | 473 | 683 | 37.7 | 49.8 | 37.7 |
| 304L | 3A14b | | | 0.25 | 0.1 | 98 | 50 | 462 | 685 | 29.7 | 42.9 | 29.7 |
| 304L | 9A19a | | | 0.25 | 0.0 | 127 | 50 | 435 | 681 | 33.2 | 48.0 | 33.2 |
| 304L | 9A19b | | | 0.25 | 0.0 | 127 | 50 | 429 | 654 | 36.8 | 47.6 | 36.8 |
| 304L | 10A23b | | | 0.25 | 0.1 | 105 | 50 | 472 | 677 | 36.5 | 48.2 | 36.5 |
| 304L | 10A23a | | | 0.25 | 0.1 | 105 | 50 | 464 | 679 | 36.6 | 49.2 | 36.6 |
| 304L | 10A23c | | | 0.25 | 0.1 | 105 | 22 | 476 | 702 | 40.6 | 59.5 | 40.6 |
| 304L | 10A23d | | | 0.25 | 0.1 | 105 | 22 | 507 | 704 | 38.9 | 59.2 | 38.9 |
| 316LN | E15 | | | 0.25 | 0.0 | | 20 | 292 | 598 | 52.9 | 58.8 | |
| 316LN | E16 | | | 0.25 | 0.0 | | 20 | 288 | 597 | 42.6 | 50.2 | |
| 316LN | 29-3-1 | 17 | 150 | 0.25 | 0.45 | 73 | 20 | 595 | 729 | 31.3 | 39.2 | |

| Alloy | ID | He (appm) | H (appm) | Thickness (mm) | Dose (dpa) | Irrad. Temp (C) | Test temp (C) | YS (MPa) | UTS (MPa) | UE (%) | TE (%) | STN |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 316L | 4-5-5 | 193 | 1641 | 0.25 | 2.6 | 54 | 50 | 823 | 831 | 0.4 | 17.4 | 0.4 |
| 316L | 4-5-6 | 177 | 1491 | 0.25 | 2.4 | 54 | 50 | 822 | 853 | 0.6 | 13.9 | 0.6 |
| 316L | 4-6-3 | 241 | 2064 | 0.25 | 2.8 | 48 | 50 | 715 | 778 | 6.5 | 18.8 | 6.5 |
| 316L | 4-6-4 | 224 | 1915 | 0.25 | 2.9 | 48 | 50 | 787 | 816 | 8.0 | 19.6 | 8.0 |
| 316L | 4-6-8 | 656 | 5609 | 0.25 | 9.3 | 68 | 50 | 820 | 884 | 0.9 | 11.1 | 0.9 |
| 316L | 4-6-7 | 674 | 5758 | 0.25 | 8.8 | 68 | 50 | 861 | 892 | 0.7 | 11.4 | 0.7 |
| 316L | 4-6-9 | 233 | 1992 | 0.25 | 2.9 | 47 | 164 | 669 | 672 | 0.2 | 10.9 | 3.6 |
| 316L | 4-6-10 | 215 | 1842 | 0.25 | 3.0 | 47 | 164 | 670 | 674 | 0.7 | 11.9 | 0.7 |
| 316L | 4-6-5 | 682 | 5826 | 0.25 | 8.7 | 72 | 164 | 830 | 836 | 0.3 | 8.3 | 0.3 |
| 316L | 4-6-6 | 664 | 5676 | 0.25 | 9.2 | 72 | 164 | 859 | 860 | 0.2 | 9.7 | 0.2 |
| 316L | 24-5-3 | 158 | 1411 | 0.25 | 2.6 | 44 | 20 | 765 | 822 | 21.0 | 30.5 | 21.0 |
| 316L | 24-5-4 | 170 | 1514 | 0.25 | 2.9 | 44 | 20 | 783 | 812 | 24.1 | 32.8 | 24.1 |
| 316L | 24-5-1 | 63 | 556 | 0.25 | 1.2 | 37 | 50 | 713 | 777 | 20.1 | 34.2 | 20.1 |
| 316L | 24-5-2 | 67 | 594 | 0.25 | 1.2 | 37 | 50 | 711 | 779 | 20.8 | 33.5 | 20.8 |
| 316L | 24-5-7 | 167 | 1465 | 0.25 | 2.9 | 44 | 50 | 751 | 796 | 0.5 | 18.9 | 11.5 |
| 316L | 24-5-8 | 180 | 1571 | 0.25 | 3.1 | 44 | 50 | 734 | 769 | 14.9 | 23.4 | 14.9 |
| 316L | 24-5-5 | 235 | 2088 | 0.25 | 3.8 | 47 | 80 | 792 | 800 | 0.4 | 13.6 | 0.4 |
| 316L | 24-5-6 | 253 | 2243 | 0.25 | 4.1 | 47 | 80 | 787 | 801 | 0.4 | 13.3 | 0.4 |
| 316L | 4-7-6 | 622 | 5424 | 0.75 | 8.7 | 120 | 22 | 879 | 930 | 0.9 | 23.4 | 15.8 |
| 316L | 4-7-5 | 605 | 5573 | 0.75 | 8.3 | 120 | 164 | 733 | 767 | 0.6 | 16.6 | 0.6 |
| 316L | 24-6-8 | 168 | 1468 | 0.75 | 2.9 | 65 | 50 | 711 | 787 | 23.9 | 38.0 | 23.9 |
| 316L | 24-6-7 | 157 | 1370 | 0.75 | 2.7 | 65 | 50 | 699 | 791 | 25.9 | 46.8 | 25.9 |
| 316L | 24-6-9 | 49 | 423 | 0.75 | 1.0 | 45 | 50 | 581 | 742 | 26.6 | 44.1 | 26.6 |
| 316L | 24-6-10 | 52 | 450 | 0.75 | 1.1 | 45 | 50 | 635 | 748 | 30.2 | 48.1 | 30.2 |
| 316L | 24-6-5 | 235 | 2091 | 0.75 | 3.8 | 70 | 164 | 643 | 686 | 0.9 | 22.9 | 4.8 |
| 316L | 24-6-6 | 253 | 2246 | 0.75 | 4.1 | 70 | 164 | 683 | 702 | 0.4 | 21.3 | 7.5 |
| 316L | 316-1 | | | 0.25 | 0.0 | | 20 | 329 | 682 | 57.6 | 70.7 | 57.6 |
| 316L | 316-2 | | | 0.25 | 0.0 | | 20 | 288 | 656 | 59.9 | 69.6 | 59.9 |
| 316L | 316-5 | | | 0.25 | 0.0 | | 50 | 283 | 593 | 48.9 | 59.9 | 48.9 |
| 316L | 316-6 | | | 0.25 | 0.0 | | 50 | 302 | 608 | 48.1 | 56.7 | 48.1 |
| 316L | 316-7 | | | 0.25 | 0.0 | | 164 | 242 | 522 | 37.8 | 45.5 | 37.8 |
| 316L | 316-8 | | | 0.25 | 0.0 | | 164 | 253 | 513 | 35.7 | 45.0 | 35.7 |
| 316L | 316-3 | | | 0.75 | 0.0 | | 20 | 308 | 659 | 57.8 | 90.7 | 57.8 |
| 316L | 316-4 | | | 0.75 | 0.0 | | 20 | 261 | 648 | 57.8 | 86.4 | 57.8 |

| Alloy | ID | He (appm) | H (appm) | Thickness (mm) | Dose (dpa) | Irrad. Temp (C) | Test temp (C) | YS (MPa) | UTS (MPa) | UE (%) | TE (%) | STN |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 316LN | 29-3-3 | 31 | 260 | 0.25 | 0.65 | 73 | 20 | 612 | 721 | 30.5 | 36 | |
| 316LN | 1-3-1 | 53 | 447 | 0.25 | 0.86 | 117 | 20 | 639 | 754 | 31.6 | 39.7 | |
| 316LN | 27-4-1 | 58 | 517 | 0.25 | 1.11 | 58 | 20 | 648 | 754 | 24 | 27.7 | |
| 316LN | 29-3-5 | 77 | 665 | 0.25 | 1.36 | 73 | 20 | 673 | 783 | 30.6 | 36 | |
| 316LN | 1-3-3 | 152 | 1299 | 0.25 | 2.43 | 117 | 20 | 773 | 820 | 16.6 | 25.5 | |
| 316LN | 27-4-3 | 146 | 1330 | 0.25 | 2.53 | 58 | 20 | 711 | 778 | 23 | 26.8 | |
| 316LN | 27-4-5 | 217 | 1965 | 0.25 | 3.64 | 58 | 20 | 775 | 805 | 20.3 | 24.7 | |
| 316LN | 1-3-5 | 825 | 6997 | 0.25 | 10.67 | 117 | 20 | 877 | 881 | 6 | 12.2 | |
| EC316LN | E19 | | | 0.25 | 0 | | 20 | 279 | 645 | 68.6 | 78 | |
| EC316LN | E51 | 34 | 274 | 0.25 | 0.54 | 39 | 20 | 636 | 769 | 30 | 39.5 | |
| EC316LN | E50 | 133 | 1111 | 0.25 | 1.87 | 94 | 20 | 837 | 865 | 15.7 | 23.7 | |
| EC316LN | E12 | | | 0.25 | 0 | | 164 | 239 | 532 | 50.6 | 59 | |
| EC316LN | E54 | 34 | 274 | 0.25 | 0.54 | 39 | 164 | 550 | 658 | 24.9 | 31.6 | |
| EC316LN | E55 | 133 | 1111 | 0.25 | 1.87 | 94 | 164 | 740 | 750 | 14.5 | 20.9 | |
| EC316LN | E17 | | | 0.25 | | | 20 | 254 | 605 | 61.3 | 70.2 | |
| EC316LN | E18 | | | 0.25 | | | 20 | 252 | 598 | 63 | 71.3 | |
| EC316LN | E11 | 0.35 | 3.29 | 0.25 | 0.026 | 179 | 20 | 394 | 668 | 42.8 | 52.6 | |
| EC316LN | E13 | 0.35 | 3.29 | 0.25 | 0.026 | 179 | 20 | 398 | 674 | 45.7 | 56.5 | |
| EC316LN | E6 | 1.97 | 20.11 | 0.25 | 0.12 | 114 | 20 | 548 | 734 | 41.6 | 52.6 | |
| EC316LN | E7 | 1.97 | 20.11 | 0.25 | 0.12 | 114 | 20 | 554 | 724 | 37.7 | 45 | |

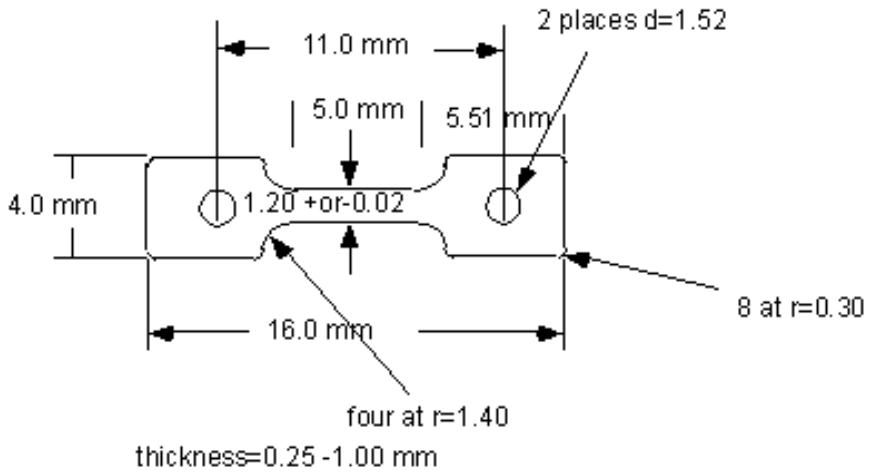


Figure 1. Schematic showing the dimensions of the S-1 tensile specimen used for measuring the tensile properties of materials after irradiation in the LANSCE irradiation facility.

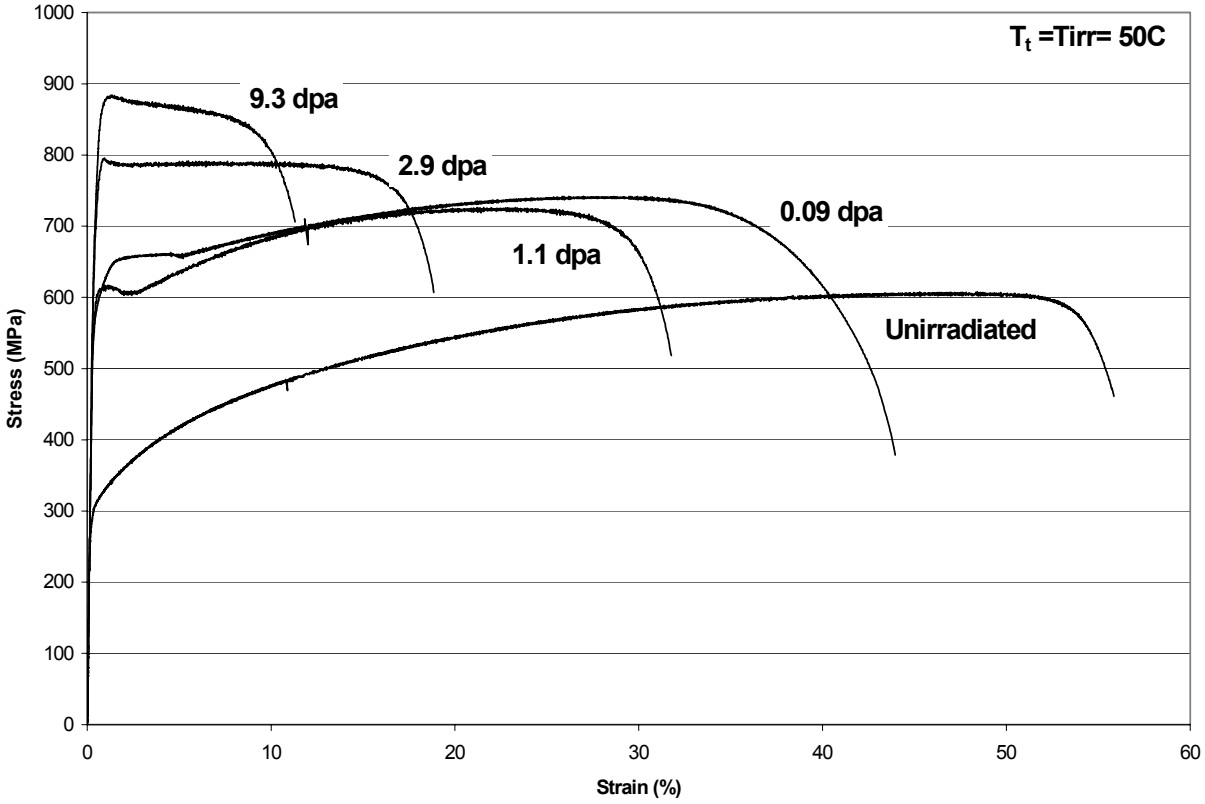


Figure 2. A plot showing stress/strain curves obtained from annealed 316L stainless steel after irradiation in the LANSCE irradiation facility.

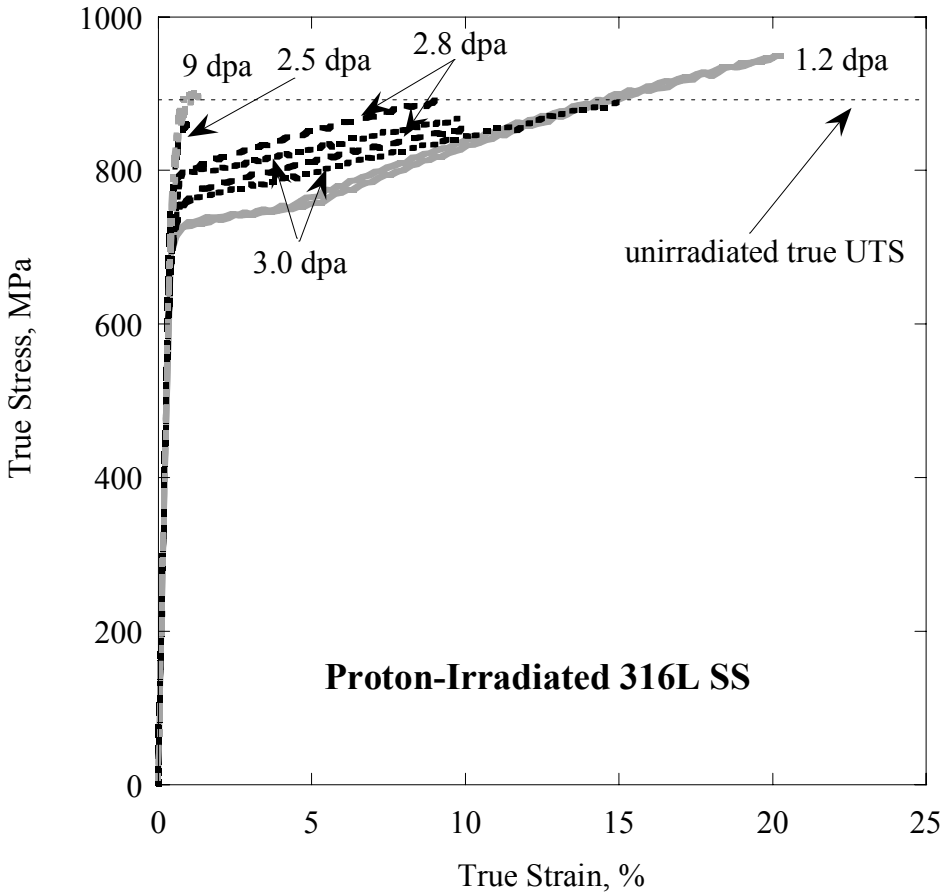


Figure 3 Graph showing True Stress vs. True Strain curves for 316L stainless steel after irradiation in the LANSCE irradiation facility.

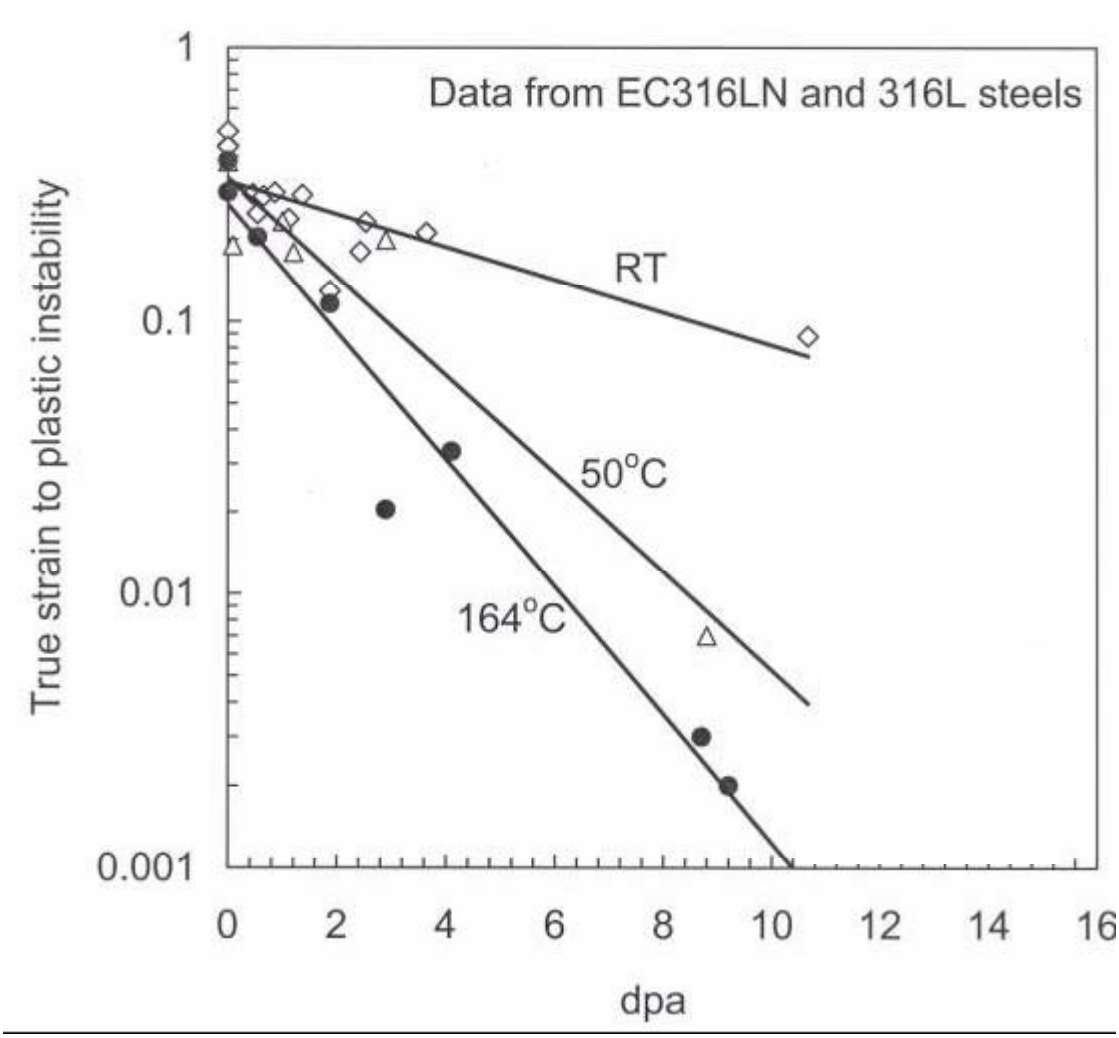


Figure 4 Graph showing True Strain to Plastic Instability measured on 316L and 316LN stainless steel after irradiation in the LANSCE irradiation facility.

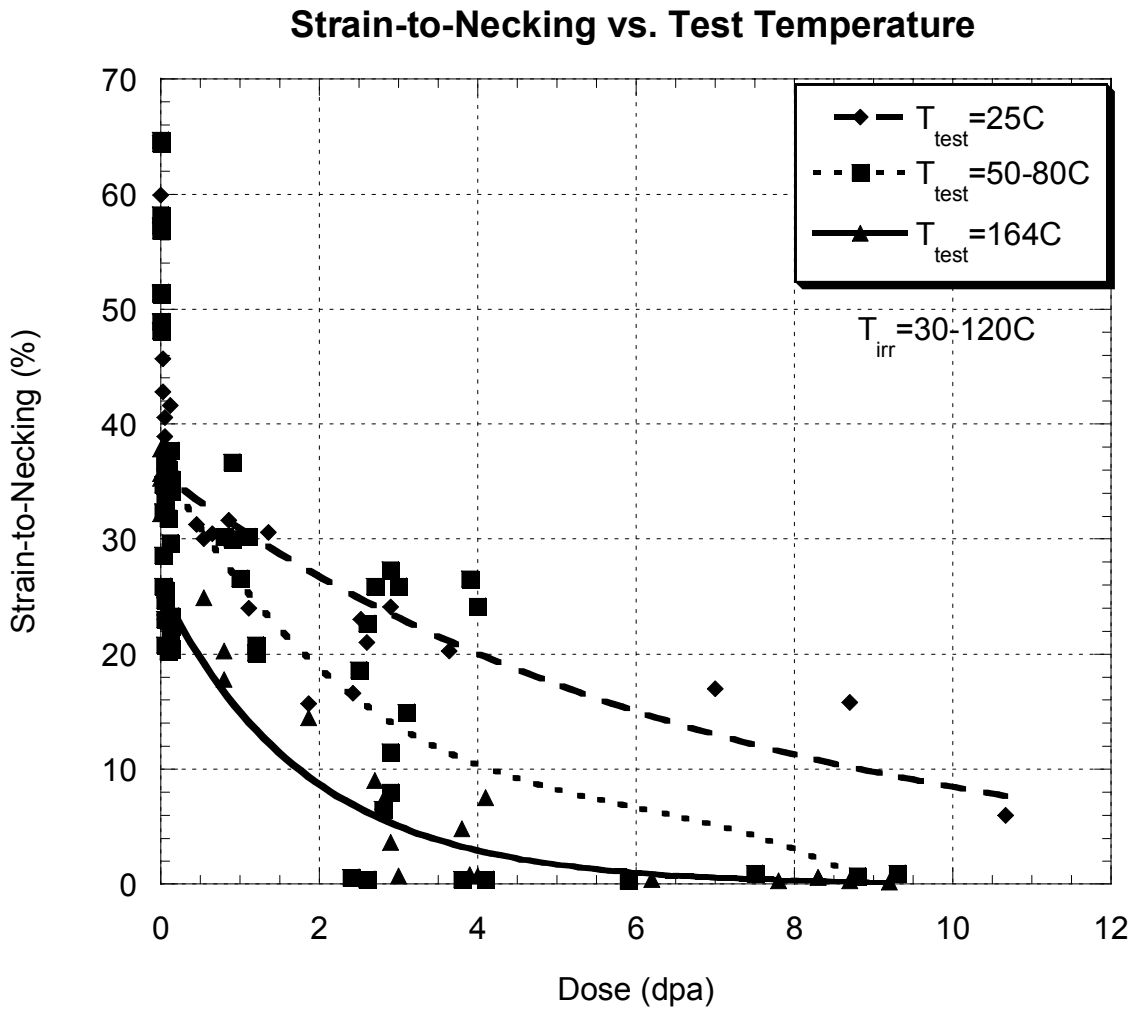


Figure 5. A graph showing the change in Strain-to-Necking with dose after irradiation in the LANSCE irradiation facility.

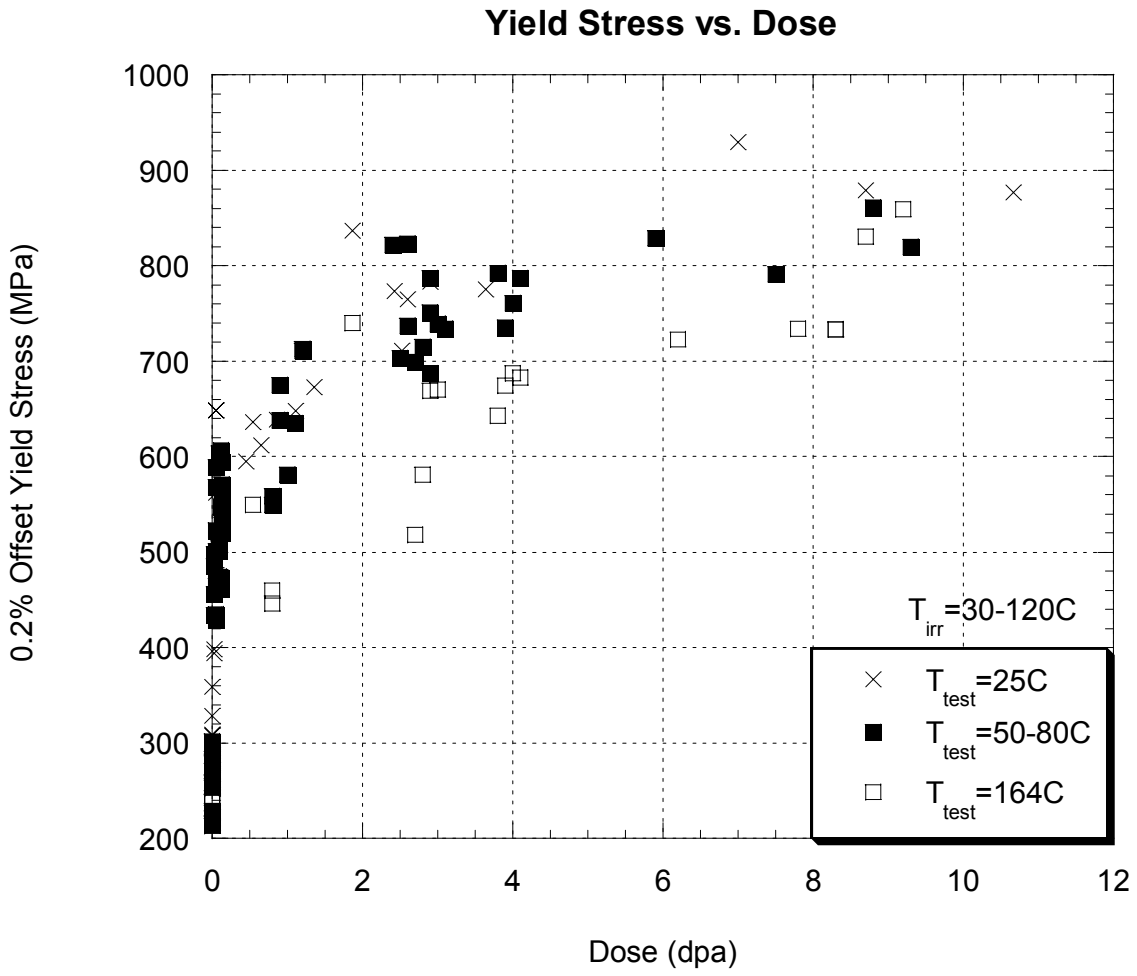


Figure 6 A graph showing the change in yield stress vs. dose for 316L/304L stainless steel after irradiation in the LANSCE irradiation facility.

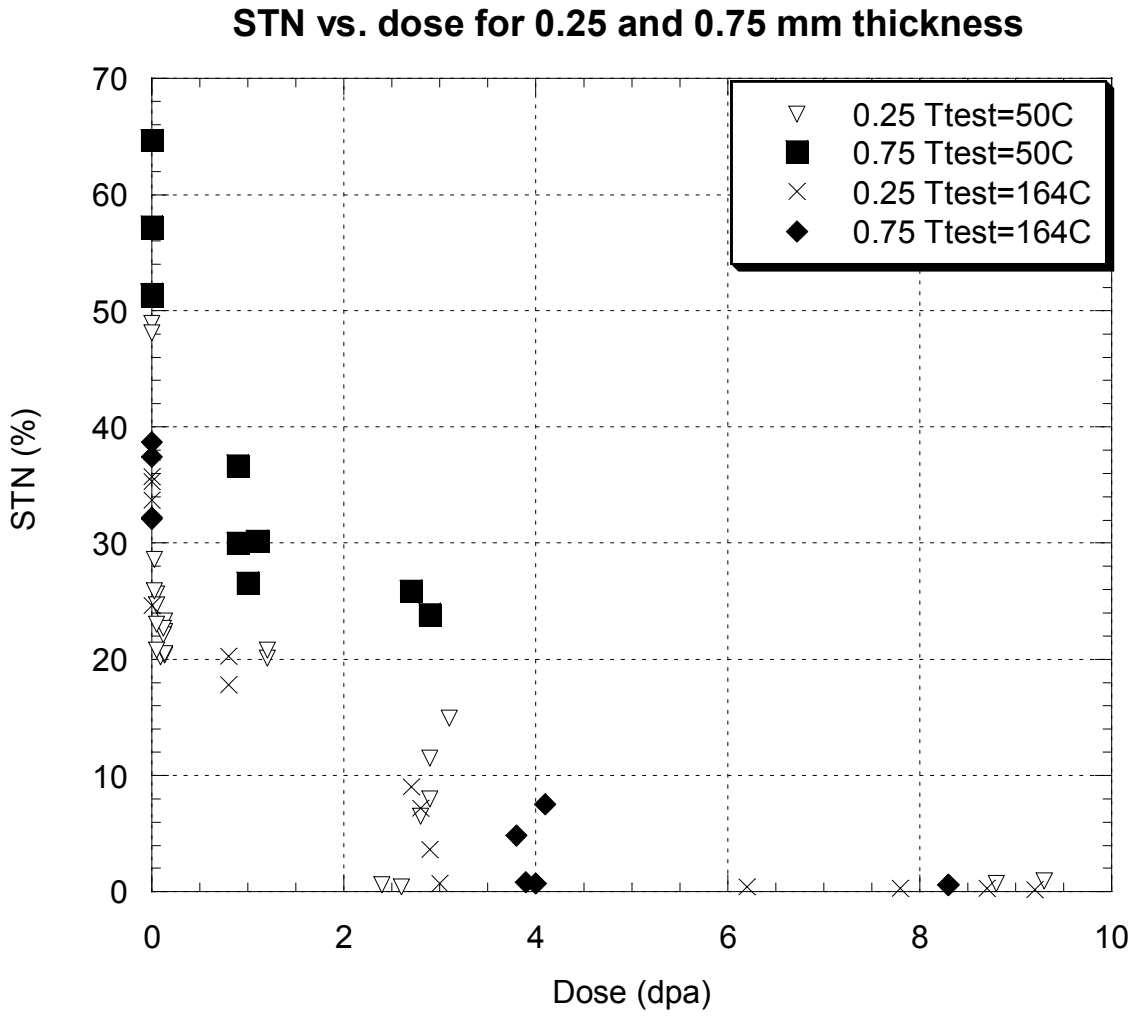


Figure 7. Graph showing variation of STN with dose for 0.25 and 0.75 mm thick specimens after irradiation in the LANSCE irradiation facility.

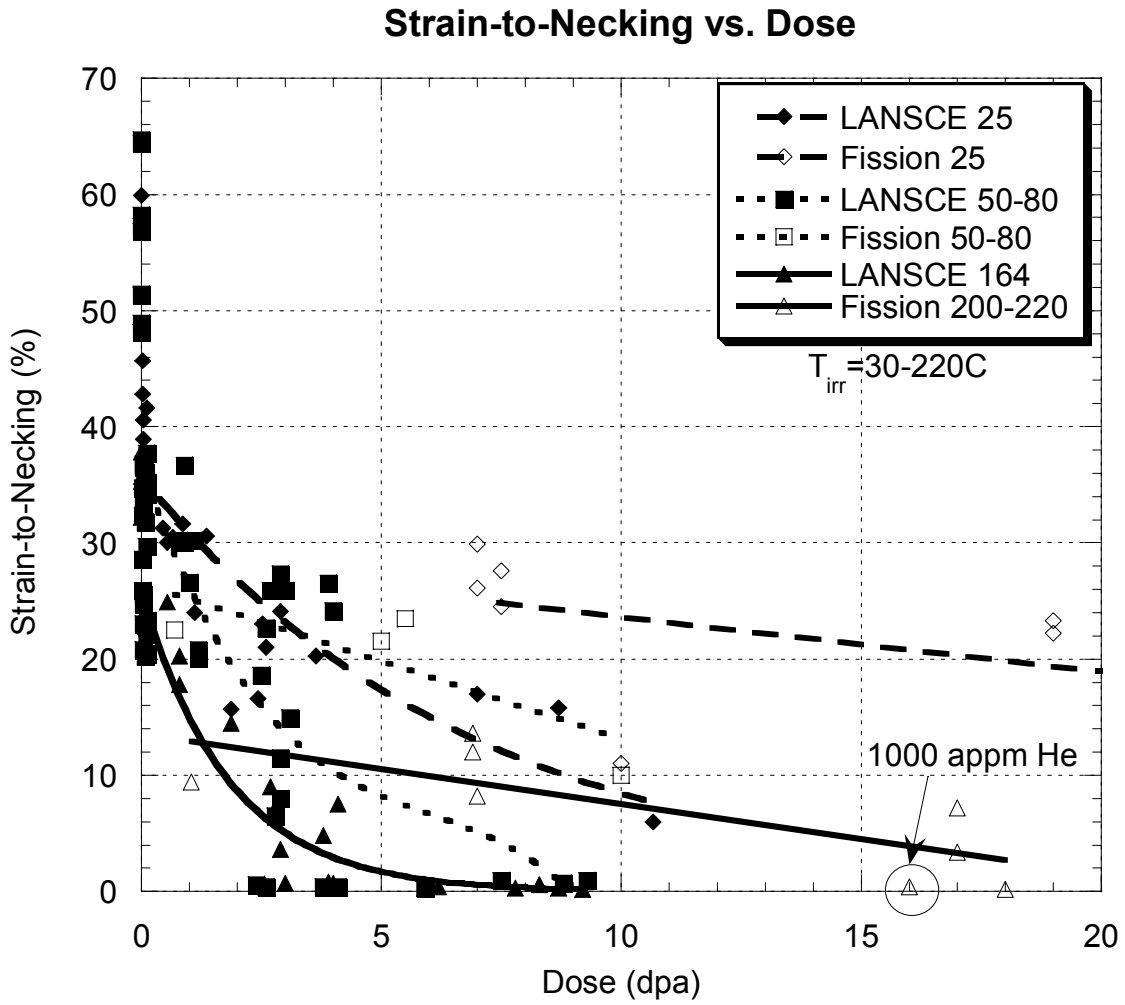


Figure 8 Graph comparing the STN measured on 316/304 stainless steel after irradiation in the LANSCE irradiation facility to that measured after irradiation in a fission spectrum.

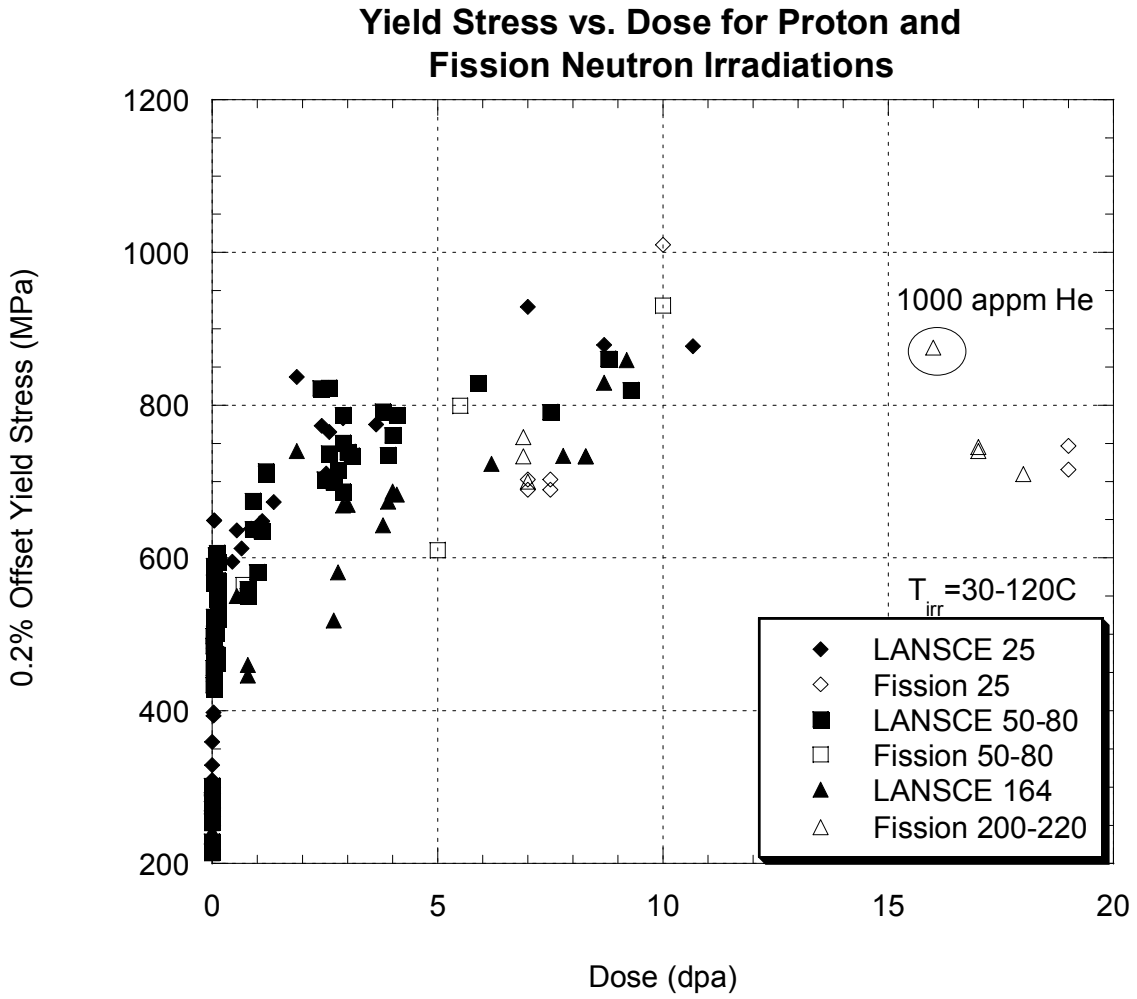


Figure 9 Graph comparing the yield stress measured in 316/304 Stainless Steel after irradiation in a fission spectrum to that measured after irradiation in the LANSCE irradiation facility.